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(54) **MESENCHYMAL STEM CELLS (MSC)  
EXPANSION METHODS AND MATERIALS**

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(51) **Int. Cl.**

**C12N 5/02** (2006.01)

**A61L 27/38** (2006.01)

**C12N 5/00** (2006.01)

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(52) **U.S. Cl.**

CPC ..... **A61L 27/3804** (2013.01); **A61L 27/3895**  
(2013.01); **C12N 5/0062** (2013.01); **C12N**  
**5/0663** (2013.01); **C12N 2500/02** (2013.01);  
**C12N 2533/90** (2013.01); **C12N 2539/10**  
(2013.01)

(58) **Field of Classification Search**

CPC ..... **A61L 27/14**; **A61L 27/38**  
See application file for complete search history.

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(57)

**ABSTRACT**

The subject invention concerns materials and methods for growing and expanding MSC while maintaining their undifferentiated phenotype, self-renewal ability, and/or multi-lineage potential. In one embodiment, a method of the invention comprises i) seeding freshly isolated MSC on a planar surface or a 3-D scaffold and growing the cells under physiological or low O<sub>2</sub> tension for a period of time sufficient to support formation of 3-D ECM network; ii) decellularizing the planar surface or 3-D scaffold; and iii) reseeding the decellularized planar surface or 3-D scaffold with MSCs, whereby the reseeded MSCs can be grown on the scaffold and maintain an undifferentiated phenotype. In one embodiment, the 3-D scaffold comprises or is composed of PET. In one embodiment, the MSC are human MSC (hMSC).

**22 Claims, 14 Drawing Sheets**  
**(6 of 14 Drawing Sheet(s) Filed in Color)**

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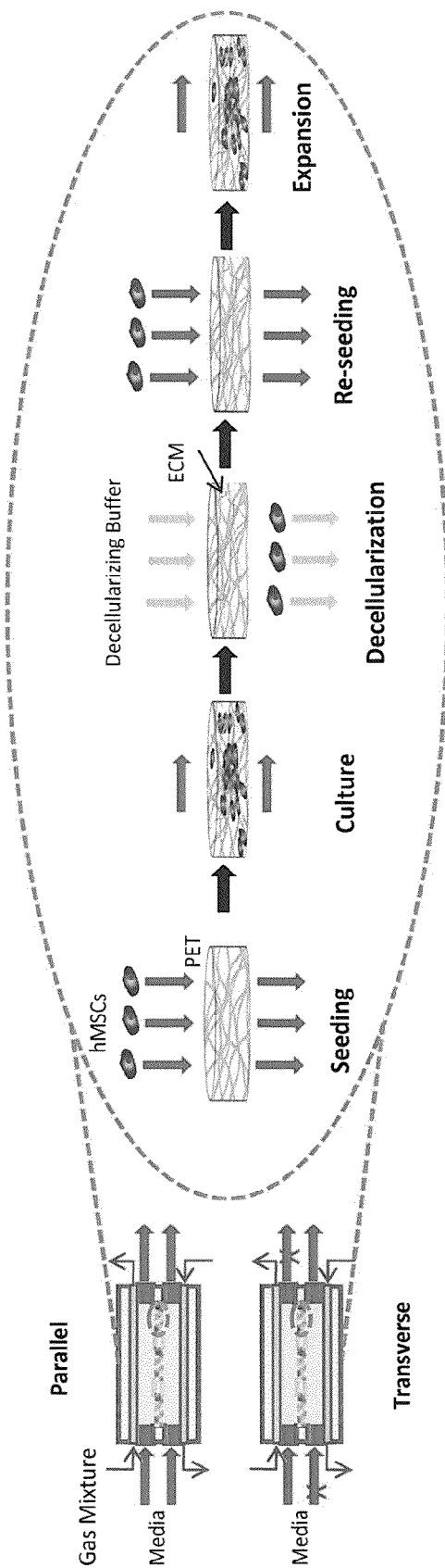


FIG. 1

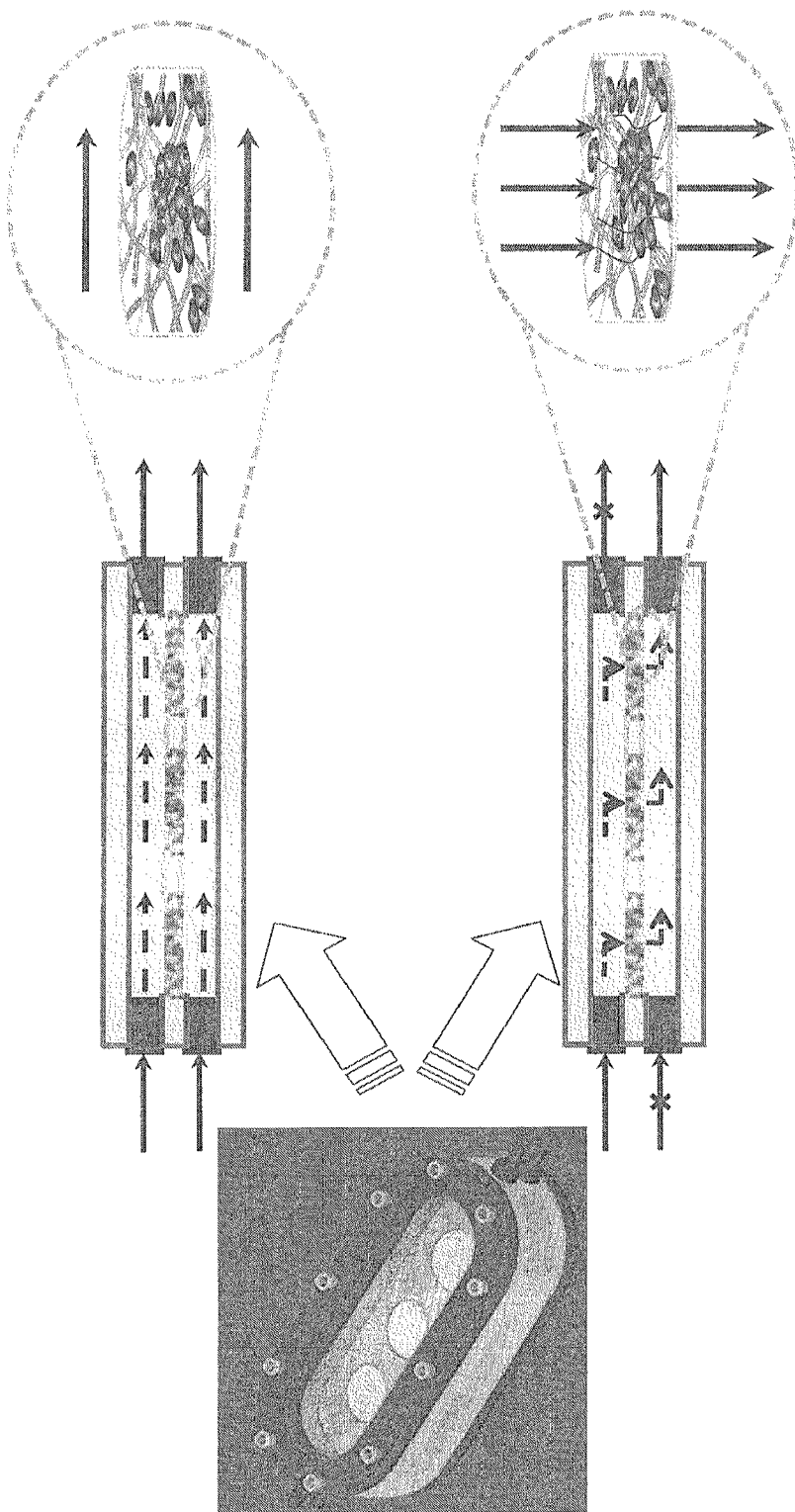


FIG. 2

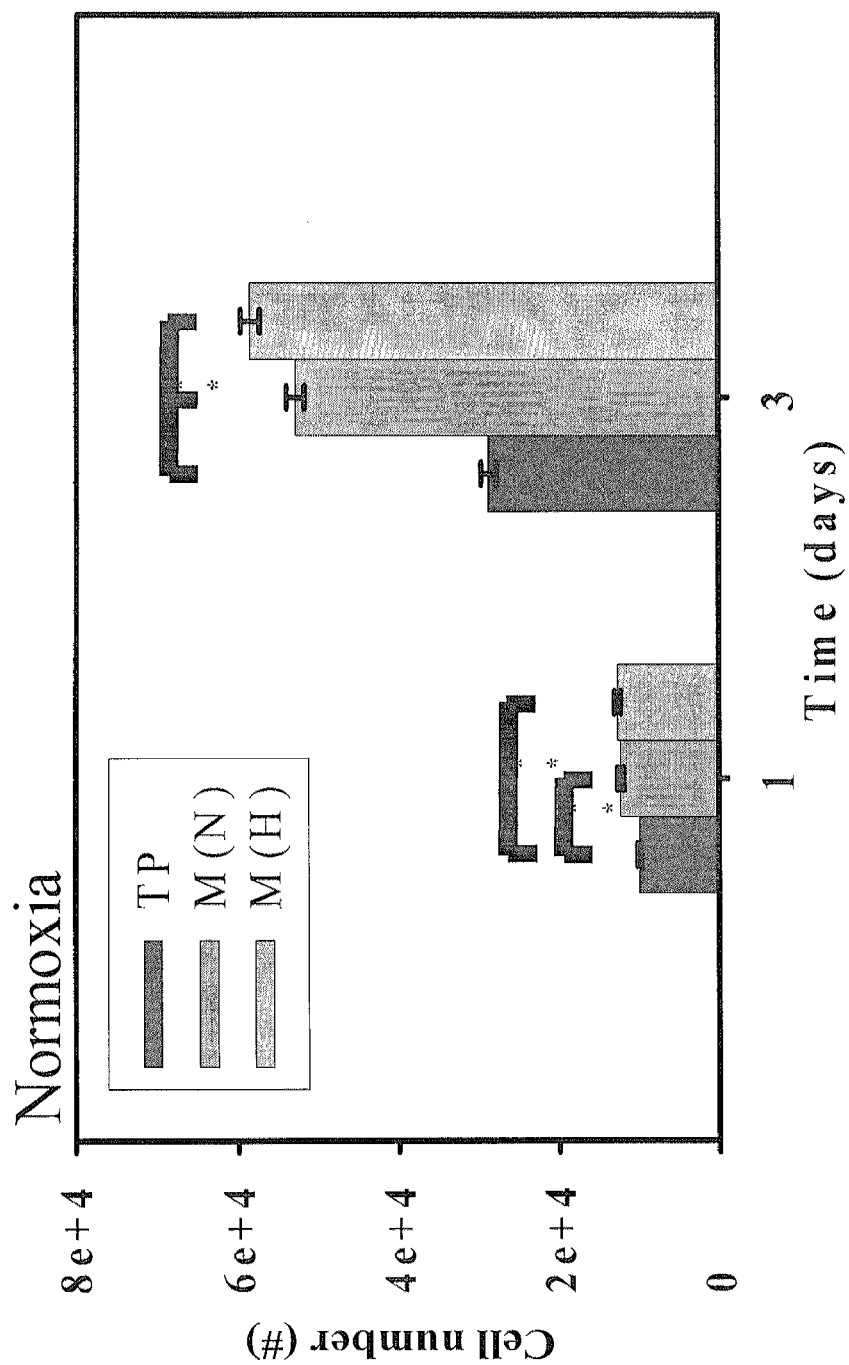


FIG. 3A-1

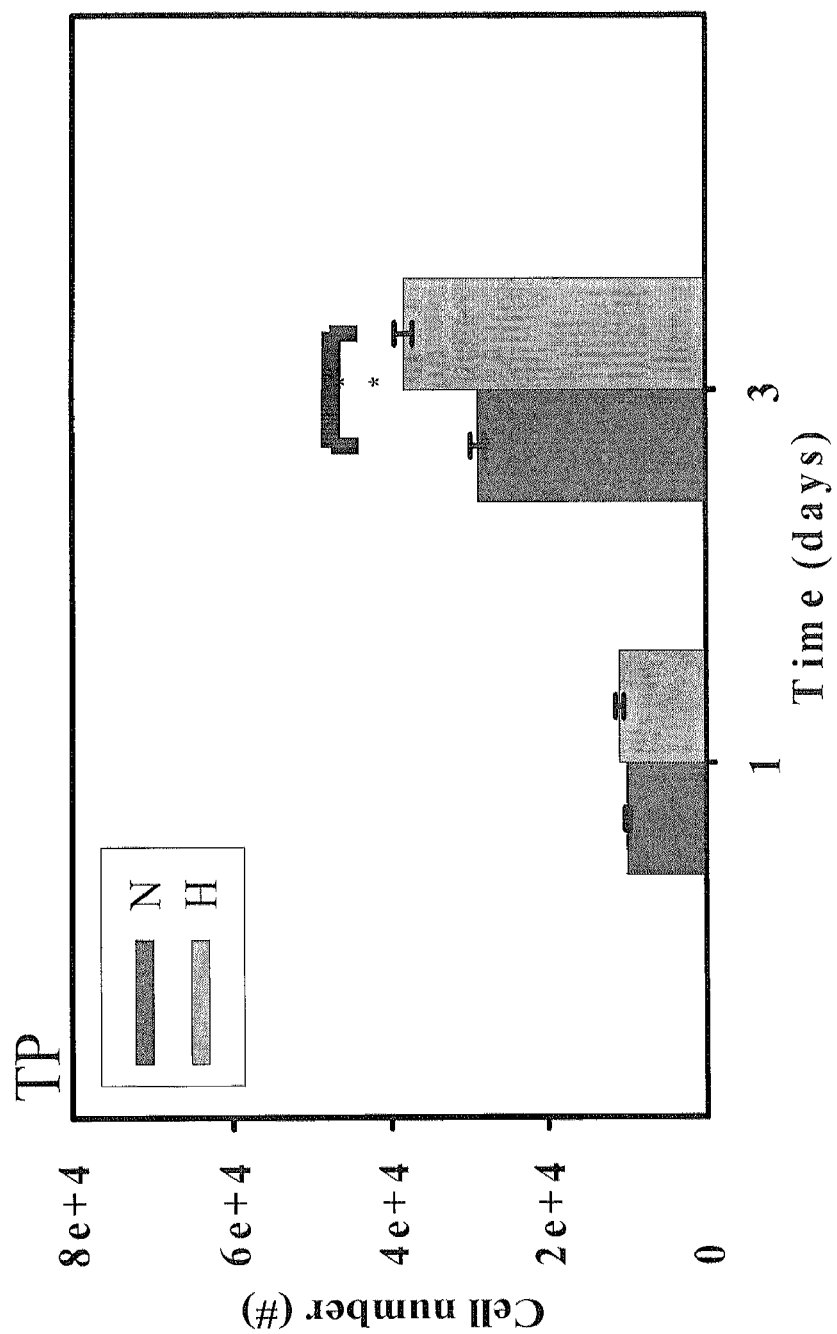


FIG. 3A-2

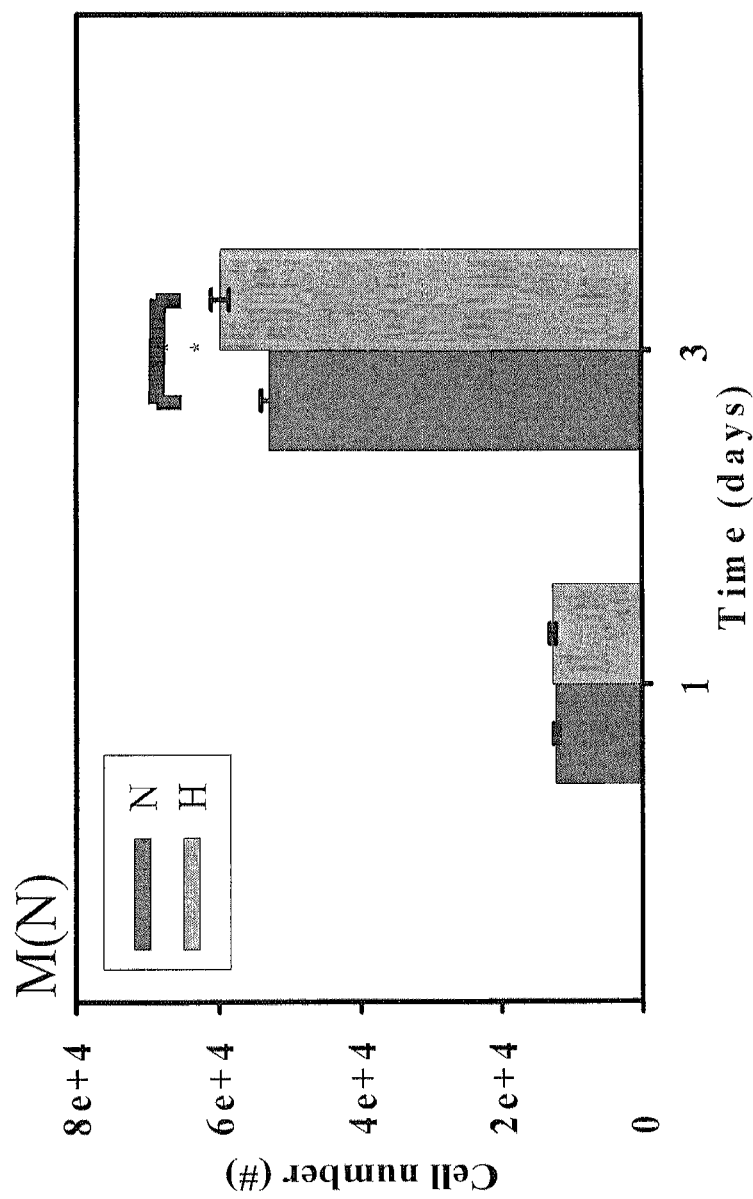


FIG. 3A-3



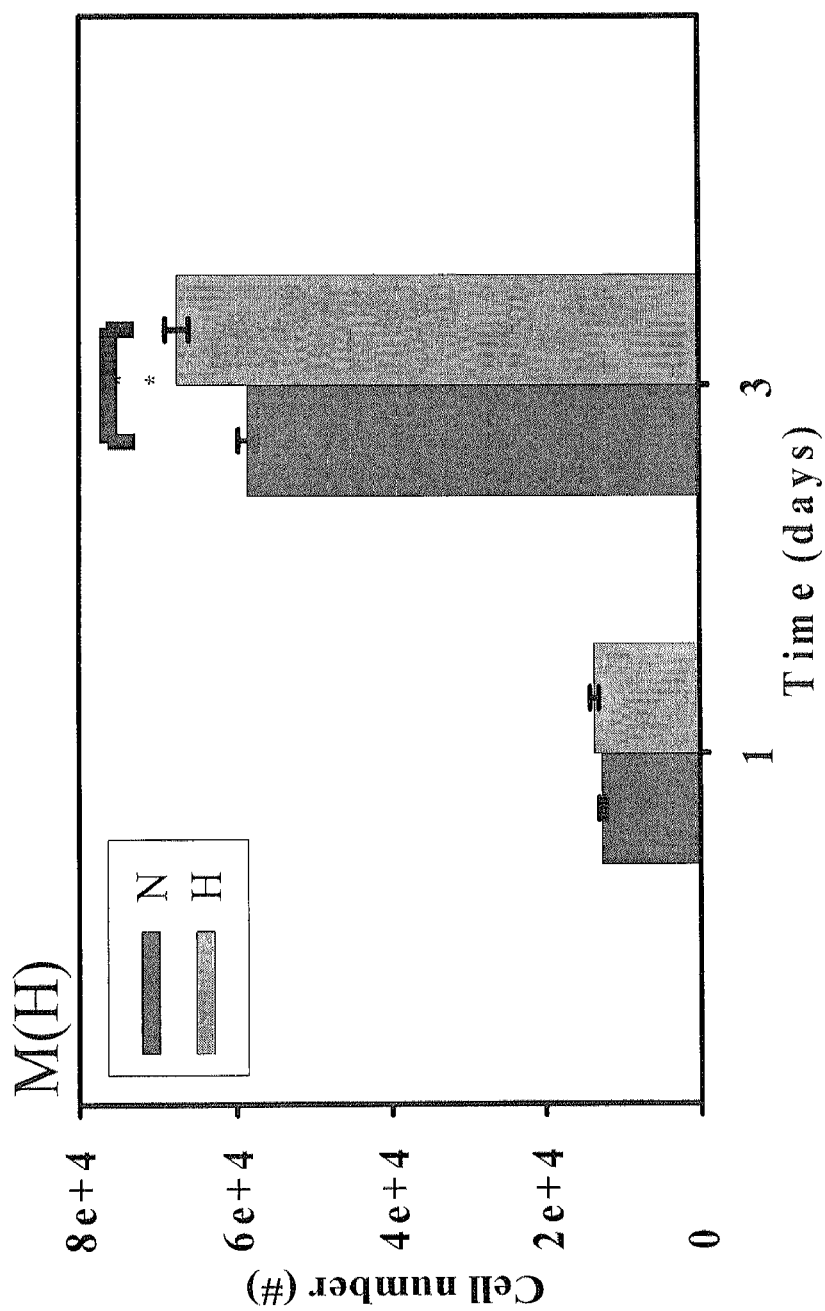
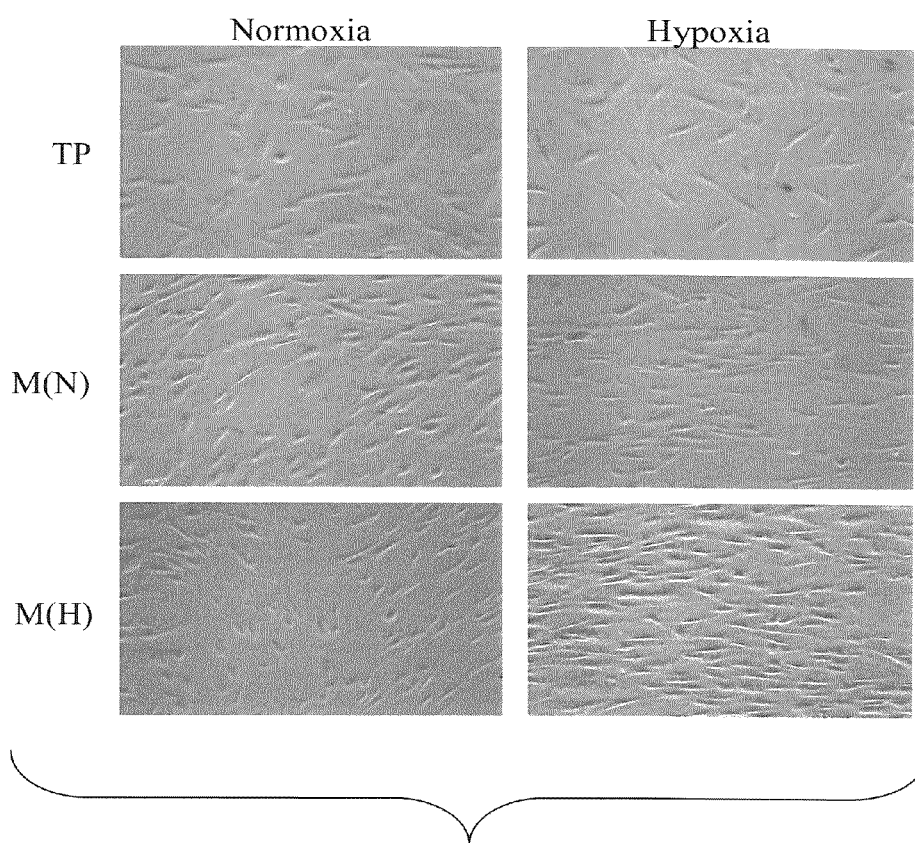


FIG. 3A-4

**FIG. 3B**

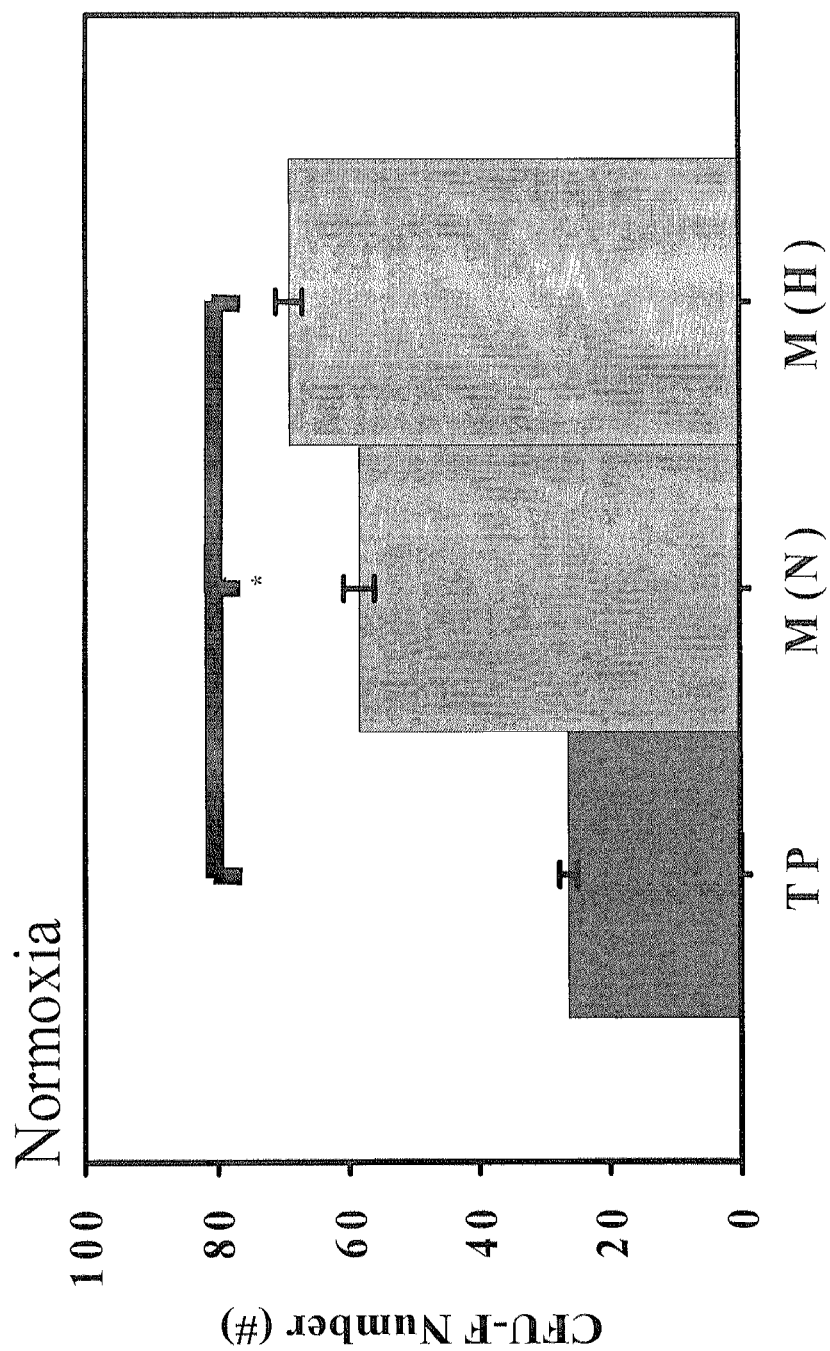


FIG. 3C-1

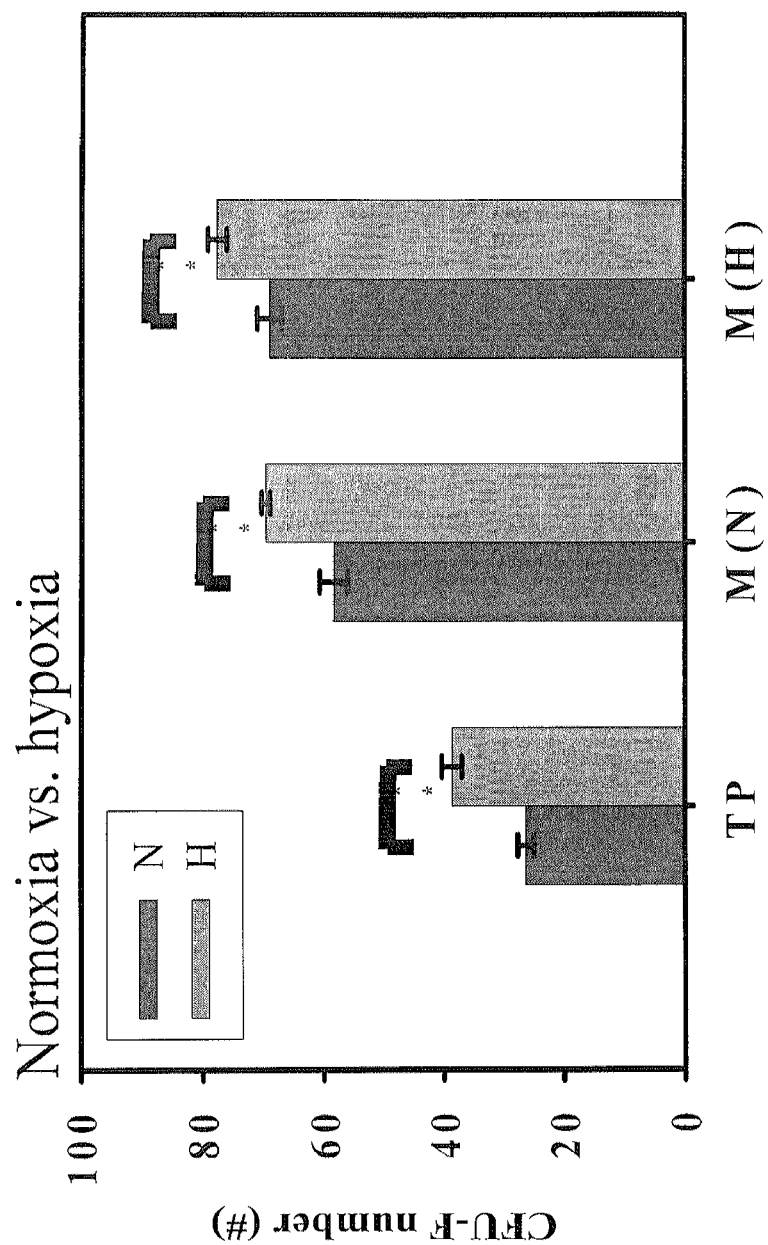
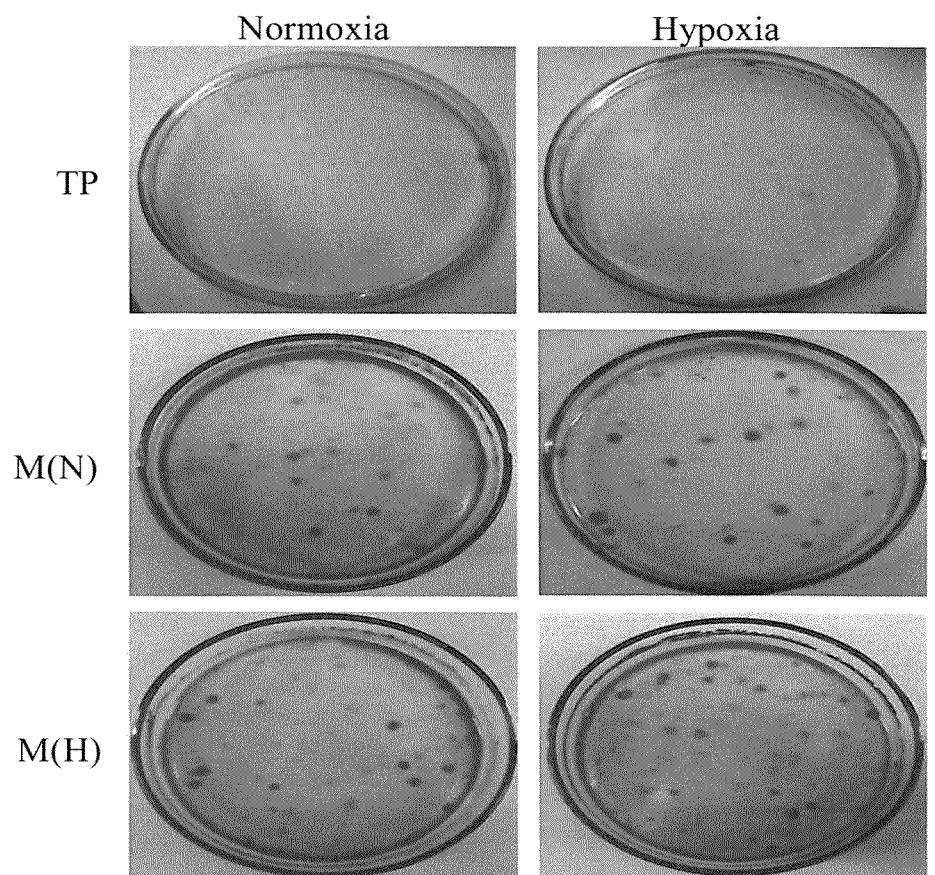
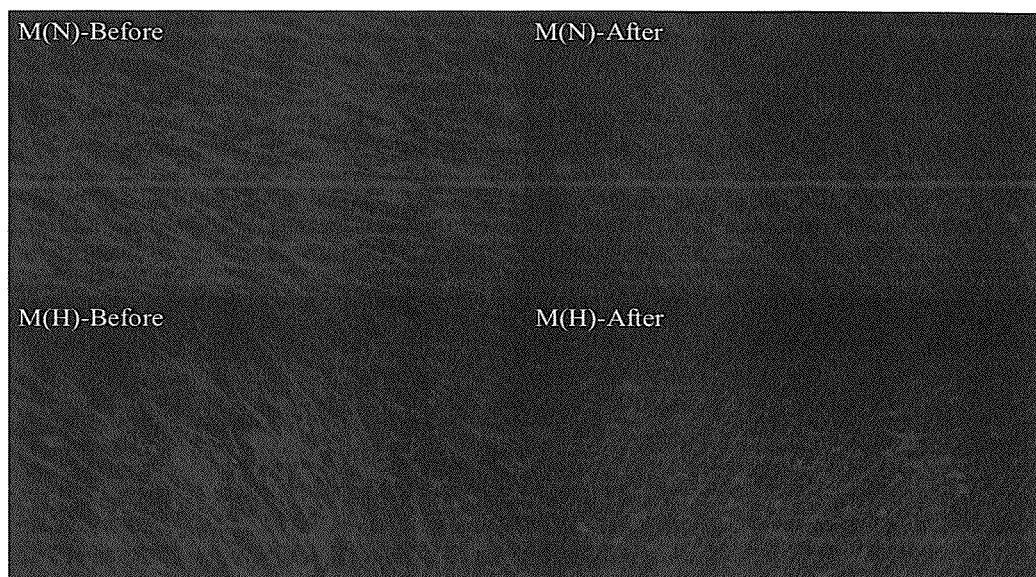
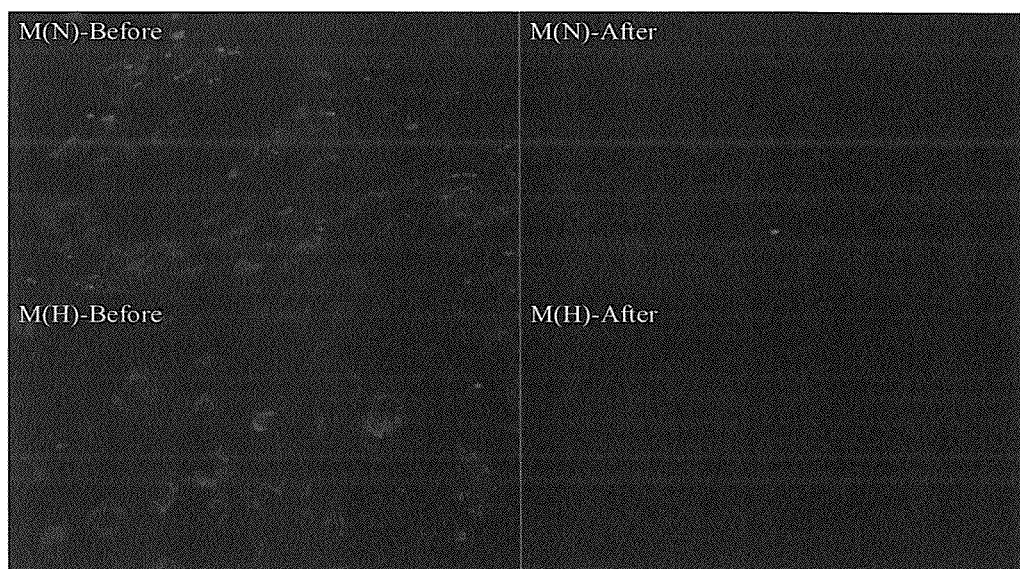
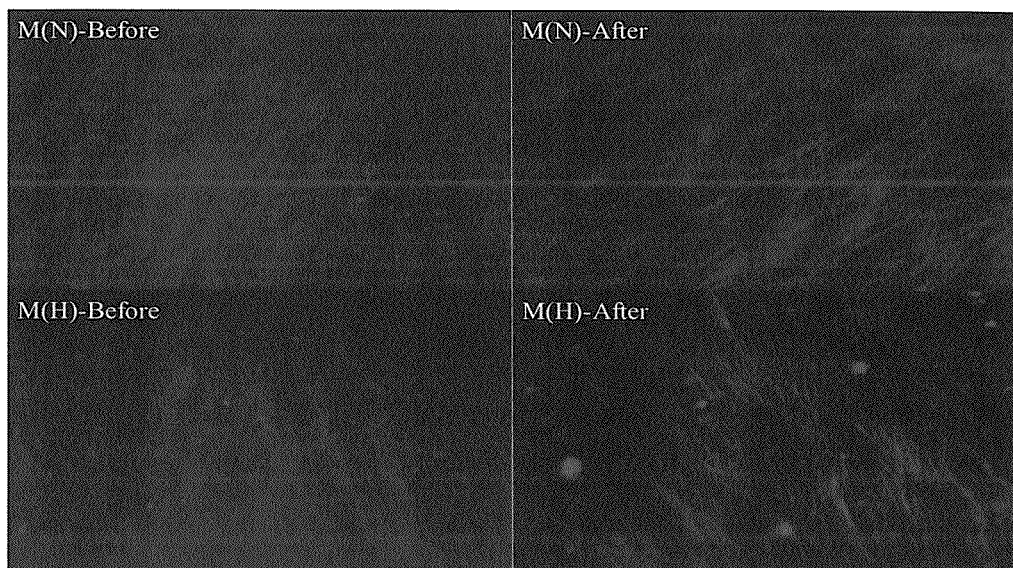
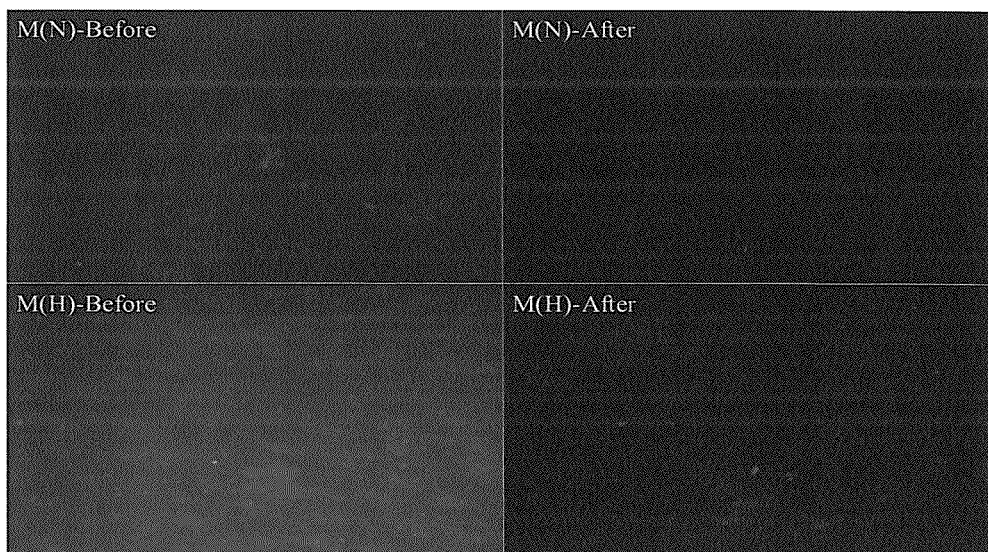


FIG. 3C-2

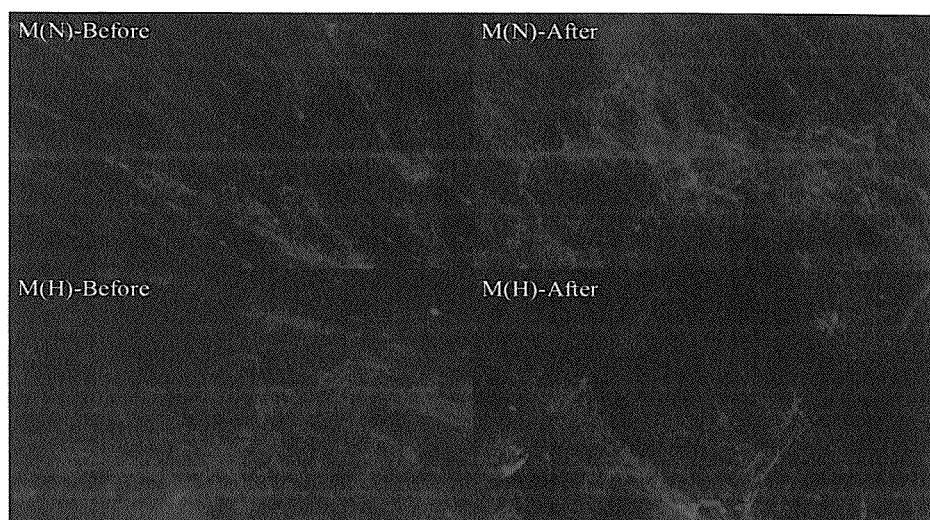


**FIG. 3D**

**FIG. 4A****FIG. 4B**

**FIG. 4C****FIG. 4D**



**FIG 4E****FIG 4F**



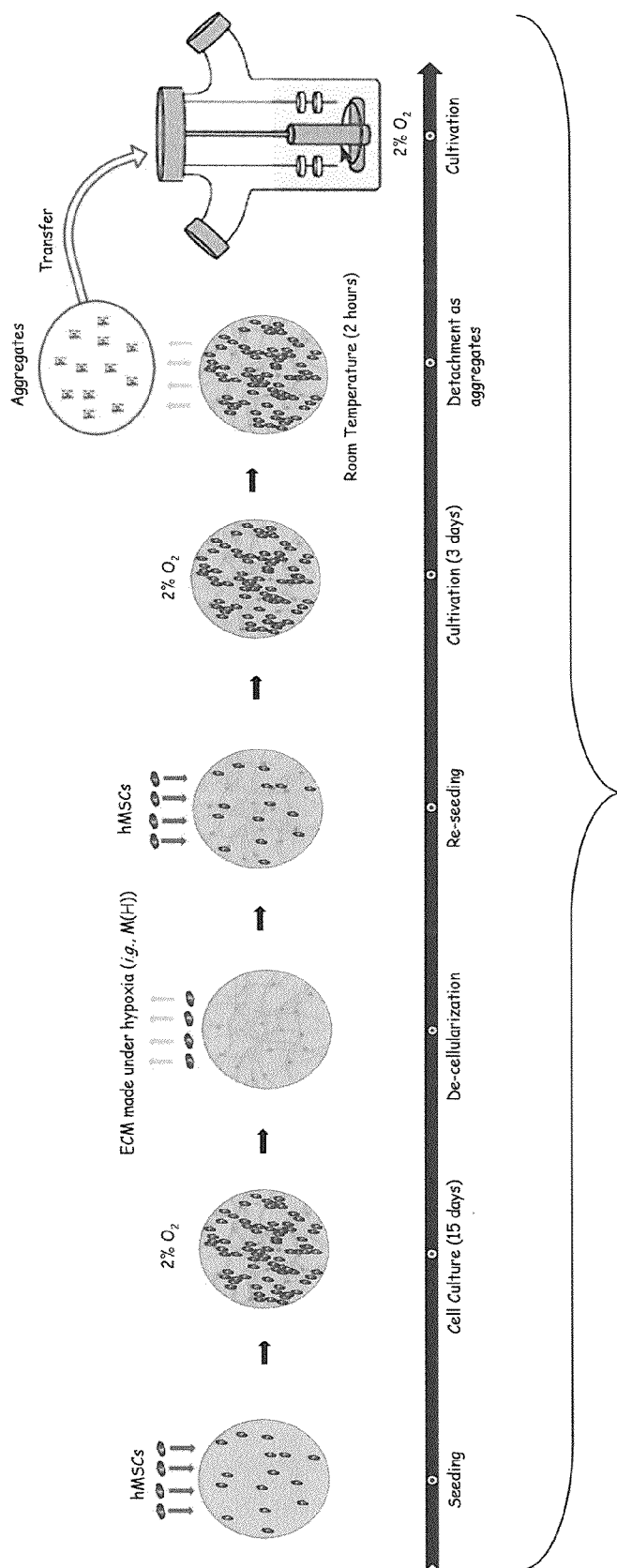


FIG. 5

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## MESENCHYMAL STEM CELLS (MSC) EXPANSION METHODS AND MATERIALS

### CROSS-REFERENCE TO RELATED APPLICATION

The present application claims the benefit of U.S. Provisional Application Ser. No. 61/421,889, filed Dec. 10, 2010, which is hereby incorporated by reference herein in its entirety, including any figures, tables, nucleic acid sequences, amino acid sequences, or drawings.

### GOVERNMENT SUPPORT

This invention was made with government support under grant number W81XWH-07-1-0363 awarded by the Department of Defense. The government has certain rights in the invention.

### BACKGROUND OF THE INVENTION

#### Introduction

Recently, human mesenchymal stem or stromal cells (hMSC) isolated from bone marrow or adipose tissue (hAMSC) (and increasingly from other tissue sources) have generated a wave of enthusiasm in both scientific and clinical communities because of therapeutic prospect for many devastating diseases (Prockop and Olson, 2007). Attractive properties of these reparative adult stem cells are that they can be readily isolated from a small tissue sample and expanded in culture and that they will home to injured tissue and enhance tissue repair (Salem and Thiemermann, 2010). To realize the potential of hMSC's in clinical applications, a significant challenge is to obtain them in sufficient quantity that they will have the required therapeutic potency (Prockop, 2009; Tang et al., 2007). Because of the low occurrence of MSC in vivo, only culture-expanded MSCs are likely to meet the demands of clinical use. Traditional cell-culture techniques facilitate billion-fold expansion of hMSCs, but result in a gradual loss of their self renewal and stem cell properties (Bruder et al., 1997). Such sequential passaging is also associated with a decrease in hMSC's responsiveness to stimuli at wound sites and reduction in their ability to secrete therapeutic factors, thus compromising the therapeutic outcome (Honczarenko et al., 2006; Son et al., 2006; Rombouts and Ploemacher, 2003). Recent studies have shown that the standard culture requires lengthy expansion to obtain sufficient quantity for transplantation, leads to genetic and epigenetic changes, and alters basic cell properties such as increasing of cell size with reduced cell mobility and therapeutic efficacy (Toma et al., 2009; Furlani et al., 2009; Lee et al., 2010; Rayment and Williams, 2010). Thus, a novel cell expansion strategy that supports robust hMSC proliferation without malignant transformation and senescence while preserving their multilineage and therapeutic potency is critical to overcome the limitation of conventional culture methods impeding hMSC's therapeutic applications.

In sharp contrast to the diminishing stem cell properties in vitro, hMSCs have remarkable in vivo self-renewal ability and multi-lineage potential over the life-time of an individual. Increasing evidence suggests that the specialized in vivo bone marrow microenvironment (ME) or niche supports MSC self-renewal and helps maintain their multi-potentiality, which are missing in the standard culture systems. The critical niche elements include extracellular matrix (ECM) proteins, growth factors (GFs), and surrounding cells. Biomechanical

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factors such as substrate rigidity as well as biochemical factors such as oxygen tension are also integral niche components and regulate stem cell behaviors (Discher et al., 2009). Considering the profound influence of the stem cell niche, recapitulating the cellular and structural components of the in vivo MSC ME has become an important approach to provide the cells with appropriate cues during expansion, thereby preserving the primitive stem cell properties. The success of the bio-inspired, engineered ME for ex vivo hMSC expansion ultimately depends on deciphering the roles of the ME components and their regulatory pathways and on successful synthesis of these multifaceted factors in an efficient and reproducible fashion.

#### MSC in Stem Cell Therapy.

Mesenchymal stem cells (MSC) isolated from bone marrow are among the most widely used stem cell types in cell therapy due to several favorable biological characteristics, including their convenient isolation from adult donors, ease of expansion while maintaining genetic stability (Bernardo et al., 2007), lack of immunogenicity and feasibility for allogeneic transplantation (Aggarwal and Pittenger, 2005; Le Blanc et al., 2003), and homing to sites of tissue injury and repair the tissue, either by differentiating into tissue-specific cell phenotypes (Zhang et al., 2007; Barbash et al., 2003; Pereira et al., 1998; Ferrari et al., 1998; Liechty et al., 2000; Dezawa et al., 2001), or by creating a milieu that modulates the immune response (Chen et al., 2001; Hofstetter et al., 2002; Ankeny et al., 2004). Culture expanded MSCs have been approved for clinical trials for treatment of numerous ailments including hematopoietic diseases (Lazarus et al., 2005; Koc et al., 2000) cardiovascular diseases (Nagaya et al., 2005; Katritsis et al., 2005) brain and spinal cord injury (Sykova et al., 2006), cartilage and bone injury (Ohgushi et al., 1989; Xian and Foster, 2006; Quarto et al., 2001) and bone and cartilage regeneration (Sakai et al., 2006). While the use of hMSCs in the clinical arena has generated great excitement (there are more than 200 clinical trials are currently exploring the application of MSC as reported at <http://clinicaltrials.gov>), significant challenges must be overcome prior to the clinical application of hMSC. First, in the bone marrow obtained from human donors, hMSC's are rare and in the range of approximately 1 in 10<sup>5</sup> nucleated cells (Bruder et al., 1997). While culture expansion is a necessary step to acquire sufficient quantities of cells for therapeutic application, culture-induced transformation is a significant barrier in stem cell-based therapy that impacts patient safety and therapeutic efficacy. hMSC in culture was shown to be associated with a diminishing proliferation rate and a gradual loss of multilineage differentiation capacity and their ability to respond to chemical stimuli (Kertlow et al., 2008; Wall et al., 2007; Banfi et al., 2000). Poor cell engraftment and migration, massive cell death and extreme low viability (<5%) post-transplantation have also been reported in the treatment of ischemic heart and brain injuries (Salem and Thiemermann, 2010; Mangi et al., 2003). Understanding hMSC behaviors in culture and developing novel strategies that promote hMSC proliferation while preserving their therapeutic potency are critically important.

Standard plastic culture-ware are typically used to expand hMSC for clinical studies, including hMSC transplantation to patients with stroke (Lee et al., 2010), acute myocardial infarction (Chen et al., 2004), and severe limb ischemia (Lasala et al., 2010). Based on current literature, conventional culture remains the prevailing method to expand hMSCs for transplantation and has been implicated for the limited success in hMSC's therapeutic applications (Prockop and Olson, 2007;

Salem and Thiemermann, 2010; Prockop, 2009; Tang et al., 2007; Lee et al., 2010; Prockop et al., 2010).

Studies have begun to reveal the adverse impact of the conventional culture method on hMSC properties, especially cell migration and survival. Sequential passaging of MSC using standard methods has been shown to be associated with a decrease in expression of adhesion molecules, the loss of chemokine receptors, enlargement of cell size, and lack of chemotactic response to chemokines, thus compromising their therapeutic potency. The culture-expanded MSCs were entrapped at the pre-capillary level because of their large size after intra-arterially delivery, leading to micro-ischemia and significant loss of cell population (Toma et al., 2009; Furlani et al., 2009). Freshly isolated murine MSCs have high efficiency for homing to bone marrow following infusion but lose their homing ability after culture expansion (Rombouts and Ploemacher, 2003). In stoke treatment, culture expanded hMSCs at passage 2 (P2) have significantly higher trophic factor secretion (e.g., VEGF, EPGF, BDNF, bFGF) as compared to those of P6 hMSCs, although both have similar morphologic features, viability, and tri-lineage differentiation capacity (Li et al., 2008). In addition, homing receptors such as CXCR4, a chemotactic receptor for SDF-1, is usually absent on the surface of culture-expanded MSCs (Karp and Teo, 2009; Sackstein et al., 2008). As a result, limited targeting capability of culture-expanded hMSC and very low graft survival rate require the delivery of a large number of cells to achieve the therapeutic effects. Because MSC's therapeutic value depends not only on multi-lineage potency but also homing and engrafting abilities, strategies are being actively sought to preserve their stemness and enhance their therapeutic potential (Kuhn and Tuan, 2010; Karp and Teo, 2009). A novel cell expansion approach that not only expands the cell population but also preserves markers and homing ability will play a pivotal role in these efforts.

The recognition that the standard culture methods are unphysiological and the need to supply hMSC in sufficient quantity have inspired the bioreactor development for MSC expansion. Micro-carrier suspension culture has been used to support MSC with comparable growth kinetics on tissue culture plastics with reduced apoptosis and improved osteogenic differentiation potential (Yang et al., 2007). Bone marrow derived cells have also been expanded in non-adherent stirred suspension culture (Baksh et al., 2007). Using a single-pass perfusion bioreactor, MSCs have also been expanded as an adherent cell layer on a 2D surface and clinical scale MSC expansion with osteogenic potential was achieved (Dennis et al., 2007; Marolt et al., 2010). While these bioreactors provide a controllable bulk growth environment, there is limited control over the microscopic cellular ME such as cell-cell and cell-material interactions, which is critical for preserving MSC properties during expansion. In addition, the biomechanical forces induced in the suspension culture system may function as a selective force on the heterogeneous MSC population and impact MSC properties and its immediate ME. We have shown that media flow even at the lower end of the physiological range can significantly bias the distribution of regulatory macromolecules due to their low diffusivity, thereby influencing the cellular outcomes (Zhao et al., 2007). Thus, the need to control the bulk macro-environmental parameters in a bioreactor system must be balanced against the needs to optimize local interactions between cells and local cellular and physiochemical ME interactions to achieve sustained MSC expansion.

hMSC ME Formation and Regulation.

hMSCs, the stromal cells in the bone marrow, are responsible for the formation of the in vivo ME that includes soluble

factors and an ECM network. The extracellular signals generated by the surrounding ME, such as cell-cell interactions, secreted and ECM-bonded GFs, molecules of ECM, and local physiological environments, work in intricate harmony to influence MSC identify and regenerative abilities. The ECM not only mediates cell adhesion but also binds GFs and so influences their spatial presentation to the cells. The functional secretions of bioactive factors are important characteristics of MSC. In fact, MSC's therapeutic potency has been attributed to the secreted bioactive factors that suppress the local immune system, inhibit apoptosis, enhance angiogenesis, and stimulate mitosis and tissue-specific differentiation (Caplan and Dennis, 2006). Referred to as trophic effects, the secreted factors have effects on cells in their vicinity either directly or indirectly, constituting an important component of the stem cell ME. Marrow ECM as well as the ECM made by cultured MSC profoundly influence MSC behaviors, from proliferation to lineage-specific differentiation and apoptosis (Chen et al., 2007; Klein, 1995). Thus, it is important to recapitulate the multifaceted niche factors as well as their dynamic interplay if any desired stem cell response is to be made robust for cell therapy.

In addition to the biological factors, one developmentally important stimulus that is still rarely accounted for during in vitro stem cell expansion is the O<sub>2</sub> tension. Although the role of O<sub>2</sub> as a metabolic substrate has been investigated extensively for cell expansion, much less studied has been the utilization of oxygen as a signaling molecule to influence stem cell behavior in culture. (In the subject application, O<sub>2</sub> levels lower than 20% are termed hypoxic and 20% O<sub>2</sub>, normoxic, for consistency with conventional terminology.) In general, MSCs exhibited greater colony-forming potential (Grayson et al., 2006; Lennon et al., 2001) proliferated longer (Grayson et al., 2007; Fehrer et al., 2007; Buravkova and Anokhina, 2007), and maintained their undifferentiated characteristics better under hypoxia conditions (D'Ippolito et al., 2006). Hypoxia is also a potent inducer for the secretion of angiogenic factors by MSCs, contributing to the therapeutic benefits (Potier et al., 2007; Sadat et al., 2007; Gneccchi et al., 2006). Hypoxia inducible factors (HIFs) are the central regulator and mediate MSC' defining features including self-renewal and multipotency in response to a low oxygen environment (Keith and Simon, 2007). Given hypoxia's essential role in hMSC behaviors, incorporating optimal oxygen conditions in the culture system can reproduce the physiological conditions (as low as 1-2% (Kofoid et al., 1985)) that contribute to adult stem cells' remarkable feat of self-renewal and the maintenance of multi-potency through adulthood. However, in contrast to the increasing knowledge of hypoxia effects on cell cycle and proliferation, the effects of oxygen tension on the macromolecular milieu of hMSC ME and its subsequent influence on hMSC properties have not been effectively incorporated in the hMSC culture expansion systems.

#### BRIEF SUMMARY OF THE INVENTION

The subject invention concerns materials and methods for growing and expanding stem cells while maintaining their undifferentiated phenotype, self-renewal ability, therapeutic potency, and/or multi-lineage potential. In one embodiment, a method of the invention comprises i) seeding freshly isolated MSC on a planar surface or a porous 3-D scaffold and growing the cells under physiological or low O<sub>2</sub> tension (e.g., lower than 20% O<sub>2</sub>) for a period of time sufficient to support formation of 3-D ECM network; ii) decellularizing the planar surface or 3-D scaffold; and iii) reseeding the decellularized

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planar surface or 3-D scaffold with MSCs, whereby the reseeded MSCs grow on the scaffold and maintain an undifferentiated phenotype. In a specific embodiment, the 3-D scaffold comprises or is composed of non-degradable polymer such as poly(ethylene terephthalate) (PET).

#### BRIEF DESCRIPTION OF THE DRAWINGS

The patent or application file contains at least one drawing executed in color. Copies of this patent or patent application publication with color drawing(s) will be provided by the Patent and Trademark Office upon request and payment of the necessary fee.

FIG. 1 shows an example of a process of the invention using a perfusion bioreactor for a streamlined hMSC ex vivo expansion process. Flow in the chamber can be controlled in either parallel (PF) or transverse (TF) to the scaffold, while O<sub>2</sub> tension is controlled by the gas mixture in the gas pouches. TF can be used for seeding and decellularization and PF for culturing. Following decellularization, freshly isolated hMSCs can be re-seeded by TF and then cultured for long-term expansion.

FIG. 2 shows an example of a perfusion bioreactor system that can be used in accordance with the present invention. The system features modular perfusion chambers with multiple sampling ports and has the capability for each chamber to be controlled individually and set for transverse (top) or parallel (bottom) flow, however, all chambers share the same media source and inoculum, facilitating comparison of various operating conditions (Zhao and Ma, 2005; Zhao et al., 2007).

FIGS. 3A-1, 3A-2, 3A-3, 3A-4, 3B, 3C-1, 3C-2, and 3D. Human MSC growth and morphologies under hypoxia or normoxia on three different surfaces, such as tissue culture plate (TP), M(N), and M(H). (FIGS. 3A-1, 3A-2, 3A-3, and 3A-4). hMSC growth on TP, M(N), and M(H) under hypoxia or normoxia. The cell numbers were higher on both M(N) and M(H) compared with ones on TP. Hypoxia further increased cell numbers on all conditions. (FIG. 3B). The morphologies were changed dramatically between on TP and on ECM matrices. Cell size was smaller on M(N) and M(H) compared with one on TP. Values are means±SD for three samples of each condition (\*:P<0.05, \*\*:P<0.01). (FIGS. 3C-1 and 3C-2). Colony forming unit-fibroblast (CFU-F). (FIG. 3D). Crystal violet staining for counting colony numbers. Colony sizes on M(N) and M(H) were much bigger than ones on TP. In addition, colony numbers on M(N) and M(H) were significantly higher than ones on TP. Hypoxia further maintained colony numbers compared with normoxia. Values are means±SD for three samples of each condition (\*:P<0.05, \*\*:P<0.01). M(N)=matrix prepared with cells grown under normoxia condition. TP=tissue culture plate. M(H)=matrix prepared with cells grown under hypoxic conditions.

FIGS. 4A-4F show components of hMSC-derived ECM visualized by immunostaining before and after cell removal. Blue represents cell nuclei and green represents ECM component. FIG. 4A shows staining for FN component. FIG. 4B shows staining for LN component. FIG. 4C shows staining for VN component. FIG. 4D shows staining for COL I component. FIG. 4E shows staining for COL III component. FIG. 4F shows staining for COL IV component. The decellularized ECM matrices maintained their structure after cell removal. Magnification, ×200. FN=fibronectin; LN=laminin; VN=vitronectin; COL I=collagen I; COL III=collagen III; COL IV=collagen IV.

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FIG. 5 shows an example of a process of the invention using tissue culture plates and spinner flask for ex vivo expansion of MSC.

#### DETAILED DESCRIPTION OF THE INVENTION

The subject invention concerns materials and methods for growing and expanding mammalian MSC while maintaining their undifferentiated phenotype, self-renewal ability, and/or multi-lineage potential. In one embodiment, a method of the invention comprises i) seeding freshly isolated MSC on a planar surface, such as plastic tissue culture plates, or on a 3-D scaffold and growing the cells under physiological or low O<sub>2</sub> tension (e.g., lower than 20% O<sub>2</sub>) for a period of time sufficient to support formation of 3-D ECM network; ii) decellularizing the cultures on the plates or the 3-D scaffold to obtain decellularized ECM matrices thereon; and iii) reseeding the decellularized matrices on the plates or 3-D scaffold with MSCs, whereby the reseeded MSCs grow on the plate or scaffold that comprises cell-derived 3-D ECM and maintain an undifferentiated phenotype. The reseeded MSCs can also be grown on the culture plates or 3-D scaffold under physiological or low O<sub>2</sub> tension. In one embodiment, the MSC cells can be grown on the planar surface or 3-D scaffold in media with low concentration (generally less than about 5% v/v) of animal serum (e.g., fetal bovine serum, human serum, etc.) or in serum-free media. In one embodiment, the reseeded MSC cultures are treated to detach the MSC and then the clusters of MSC and ECM matrices are transferred to a spinner flask and cultured in suspension. In one embodiment where a culture plate or scaffold comprises thermally responsive film or coating, the plate or scaffold is placed at room temperature or lower than room temperature (e.g., 4° C.) for a period of time (e.g., for about 1, 2, 3, 4, or more hours) and the cells are released as clusters and then transferred to a spinner flask. The cell clusters can then be cultured in suspension in the spinner flask. In one embodiment, the MSC are grown in the spinner flask under physiological or low O<sub>2</sub> tension.

In one embodiment, the MSC are grown on the planar surface or 3-D scaffold wherein the O<sub>2</sub> tension is maintained at between about 1% and 10%. In a specific embodiment, the O<sub>2</sub> tension is maintained at between about 1% and 5%. In a more specific embodiment, the O<sub>2</sub> tension is maintained at between about 1% and 3% (e.g., O<sub>2</sub> tension could be about 1%, 2%, or 3%).

In one embodiment, the planar or scaffold surface is one that has a thermoresponsive film that allows for cell detachment from the surface by modulating the temperature. Examples of thermoresponsive films include N-isopropylacrylamide, poly(allylamine hydrochloride)-co-poly(N-isopropylacrylamide), and poly(styrene sulfonate)-co-poly(N-isopropylacrylamide), and are described in Liao et al. (2010). In one embodiment, the surface comprises multiple layers of one or more thermoresponsive films. The thermoresponsive films can optionally comprise a terminal coating of a layer of positively charged allylamine hydrochloride (PAH), or negatively charged styrene sulfonic acid (PSS), or serum, such as fetal bovine serum (FBS).

In a specific embodiment, decellularization is performed using a detergent (e.g., Triton-X) and an enzyme that degrades nucleic acids (e.g., a DNase). Any suitable method for decellularizing the plate or 3-D scaffold is contemplated for use in the subject invention. In a specific embodiment, prior to decellularization, the MSC on the plate or 3-D scaffold are washed (e.g., with phosphate buffered saline (PBS)).

Expanded MSCs can be harvested following reseeding and growth of MSC. In one embodiment, MSC can be harvested

up to 3 months following reseeded. In a specific embodiment, the MSCs used in the subject methods are human MSC (hMSC). In one embodiment, MSC for use in the invention can be isolated from bone marrow and/or adipose tissue of a mammal or human. In one embodiment, the MSC population obtained following the expansion of the reseeded cells exhibits enhanced Akt and/or ERK1/2 activity.

The methods of the present invention provide for more rapid expansion of MSC population than conventional methods while preserving their native properties. ECM prepared under hypoxic (i.e., 2% O<sub>2</sub>) and normoxic conditions were used in a colony forming unit-fibroblast (CFU-F) assay as described (Grayson et al., 2006) as shown in FIG. 3. Cells seeded on M(H) and grown under hypoxic conditions significantly increased CFU-F formation as compared to cells seeded on M(H) and grown under normoxic conditions or cells seeded on M(N) and grown under hypoxic conditions. In clinical applications, shortening the time required for autologous cell expansion is critical for transplantation. The subject invention also better maintains their survival and preserves the secretion of the therapeutic factors and thus their therapeutic potency compared to traditional culture methods. In addition, the methods of the subject invention utilize a lower serum concentration or patient-specific plasma than traditional culture methods. The presence of ECM matrices also better preserves hMSC viability and enhances their proliferation in serum-free media. The ability to use plasma from a patient can reduce the risk associated with exogenous proteins, such as serum proteins.

The 3D decellularized matrices can be constructed on planar surfaces, such as glass or plastic tissue culture plates (e.g., polystyrene), or in 3-D non-degradable scaffolds that are suitable for cell culture. The planar culture surfaces contemplated within the scope of the invention include those having a thermal responsive surface that release a cell and/or cell sheet at reduced temperature without enzymatic treatment. The 3D scaffolds of the invention include but are not limited to poly(styrene), poly(carpolactone), and nylon scaffolds. In a specific embodiment, the 3-D scaffold of the invention comprises or is composed of poly(ethylene terephthalate) (PET). In one embodiment, the MSCs are grown on the 3-D scaffold in a perfusion bioreactor. One embodiment of the subject invention is shown in FIG. 1. The PET scaffolds can have an isotropic fibrous structure with a porosity of about ~90%, an average pore diameter of 50-100 µm, and a fiber diameter of 20 µm. As shown in FIG. 1, three disks of PET scaffolds (diameter: 1.6 cm; thickness: 1.2 mm) are placed in the center of the perfusion chambers (width: 2.0 cm; length: 6.0 cm), partitioning the chamber into two identical compartments and allowing media flow either parallel or transverse to the scaffolds. The ability to modulate macroscopic flow in the perfusion chambers is an important feature of the perfusion bioreactor system described in U.S. Pat. Nos. 6,875,605 and 6,943,008 and Zhao et al. (2005), and is uniquely suited to achieve the automated cell seeding, decellularization, re-seeding of the freshly isolated MSC, and final cell harvesting in a single unit. The controlled convective flow in the perfusion chamber not only improves spatial cell distribution during seeding and re-seeding, but will also improve decellularization efficiency. The outcome of this is a novel, streamlined bioreactor-based cell expansion process that supports clinical scale MSC expansion.

PET is one of the earliest biomaterials approved as implantable materials for medical uses (Homsy et al., 1968; Klinge et al., 1998; Soares et al., 1996; Vinard et al., 1988; Riepe et al., 1997; Illingworth et al., 1998; Tweden et al., 1997). Non-woven PET scaffolds have excellent chemical

and mechanical stability, and have been used as scaffolds to support the expansion of human hematopoietic stem cells and high density hMSC growth in the perfusion bioreactor (Grayson et al., 2004; Zhao and Ma, 2005; Zhao et al., 2007; Li et al., 2001). PET scaffolds' excellent biocompatibility and highly porous structure are ideal and an extensive ECM network can be formed and maintained in a structurally stable environment.

A perfusion bioreactor device of the invention can be used to grow cells and tissue in a controlled in vitro environment (see, for example, FIG. 2). Perfusion bioreactor devices that can be utilized with the present invention include those described in U.S. Pat. Nos. 6,875,605 and 6,943,008. In one embodiment, a perfusion bioreactor device of the invention can have multiple perfusion chambers that can be controlled individually. Transverse or parallel flow of a fluid can be provided to each chamber. The fluid is one that is capable of providing appropriate conditions for cell life and/or supporting and directing growth and/or differentiation of cells within the device. For example, the fluid can be a fluid containing nutrients and other chemicals or factors, such as cytokines, to support the growth and/or differentiation of cells. In one embodiment, the perfusion bioreactor chamber has two or more compartments connected by a porous scaffold (onto which cells can be seeded), and conditions such as substance concentration, pressure, and fluid flow rate can be individually controlled in each compartment. The pressure in each chamber can be regulated so that the fluid can penetrate the scaffold transversely or horizontally on demand. The porous scaffold in the chamber supports cell growth and fluid penetration thereby providing space for the cells to form a functional tissue such as bone, cartilage, or tendon. In one embodiment, the porous scaffold is a porous hydrogel and/or 3D scaffold to provide a 3D environment in the bioreactor device where the cells can adhere, proliferate, migrate, secrete growth and/or differentiation factors, and/or undergo differentiation, etc. In one embodiment, a hydrogel and/or 3D scaffold comprises PET. The hydrogel or scaffold can optionally be provided in a shape that mimics or is similar to the shape of the tissue that is to be repaired or replaced in a human or animal. In addition, the pore size of the hydrogel or scaffold can be controlled and selected to promote growth of cells.

The subject invention also concerns isolated mammalian MSC that exhibit undifferentiated phenotype, self-renewal ability, and/or multi-lineage potential that have been produced using a method of the present invention. In a specific embodiment, the MSC are human MSC. The isolated MSC can be used to treat disease in a human or animal, and to repair injured tissue. In one embodiment, the MSC exhibit enhanced Akt activity and/or ERK1/2 activity.

The subject invention also concerns a planar surface or a 3-D scaffolds that have been prepared by seeding freshly isolated MSC on a planar surface or 3-D scaffold and growing the cells under physiological or low O<sub>2</sub> tension as described herein and for a period of time sufficient to support formation of a 3-D ECM network, followed by decellularizing the planar surface or 3-D scaffold as described herein. The prepared planar surface or 3-D scaffold can then be used to grow and expand MSC that are reseeded on the planar surface or 3-D scaffold. The subject invention also concerns a planar surface or 3-D scaffolds that have the reseeded and expanded MSC thereon that exhibit an undifferentiated phenotype, self-renewal ability, and/or multi-lineage potential. In one embodiment, the scaffold is in a shape that mimics the shape of a tissue to be repaired or replaced. In a specific embodiment, the 3-D scaffold comprises PET. In one embodiment, the MSC are grown on the 3-D scaffold in a perfusion bioreactor.

An example of a claimed embodiment of the invention is shown below:

A method comprising i) seeding freshly isolated MSC on a 3-D scaffold and growing the cells under physiological or low O<sub>2</sub> tension (e.g., lower than 20% O<sub>2</sub>) for a period of time sufficient to support formation of 3-D ECM network; ii) decellularizing the 3-D scaffold; and iii) reseeded the decellularized 3-D scaffold with MSCs, whereby the reseeded MSCs grow on the scaffold that comprises cell-derived 3-D ECM and maintain an undifferentiated phenotype.

#### Materials and Methods

##### hMSCs.

Commercially available adult human bone marrow-derived MSCs are used in the study. For normoxic cultures, hMSCs may be cultured at 95% air (20% O<sub>2</sub>)—5% CO<sub>2</sub>. For hypoxia studies, hMSCs may be cultured in the custom-made cell culture chambers that are flushed with humidified gas mixtures of three different oxygen compositions: 1% O<sub>2</sub>—5% CO<sub>2</sub>—94% N<sub>2</sub>, 2% O<sub>2</sub>—5% CO<sub>2</sub>—93% N<sub>2</sub>, and 3% O<sub>2</sub>—5% CO<sub>2</sub>—92% N<sub>2</sub>. hMSC may be continuously cultured under these conditions for up to 30 passages. We have successfully used these cell culture chambers in our prior studies (Grayson et al., 2006; Grayson et al., 2007).

##### hMSC Seeding and Growth in the 3D Perfusion Bioreactor.

The in-house 3D PET perfusion bioreactor system may be modified with addition of gas pouch on each side of the chamber to control O<sub>2</sub> and pH using gas mixture (FIG. 1). The system with 4 individual chambers may be used for the experiments, following an established procedure in our lab (Zhao et al., 2009; U.S. Pat. No. 6,875,605; U.S. Pat. No. 6,943,008; Zhao et al., 2005). Spatial distribution after cell seeding may be determined by histology and cell growth may be determined by DNA assay.

##### Decellularization of 3D Construct by Perfusion.

At days 14 and 21 after seeding, the media may be removed from the bioreactor chambers. By operating the bioreactor in TF, the constructs will be first washed with PBS, then the decellularization solution containing Triton-X and NH<sub>4</sub>OH in PBS, and finally the solution containing DNase. The composition of the perfusion decellularized constructs may be analyzed using ELISA and Western blot. Based on the results, the effects of flow rate and incubation time on ECM composition may be evaluated.

##### hMSC Re-Seeding and Long-Term Expansion.

After decellularization, the freshly isolated hMSC at a predetermined density may be re-seeded in each chamber at a flow rate of 0.1 mL/min and continuously cultured. At days 1, 7, 14, and 21 after re-seeding, one chamber may be removed at each day to collect cell samples. Day 1 samples may be used to determine re-seeding efficiency and spatial distribution while the subsequent samples for cellular and molecular assays.

##### Control Experiments and Statistical Comparison.

Parallel to the perfusion bioreactor with decellularized matrices, both (1) PET bioreactor control and (2) ECM control experiments can be carried out for comparison. In PET bioreactor control, hMSC at same passage and density are seeded onto PET scaffolds alone and culture under same oxygen tension and sampled over same period. For the ECM control experiments, hMSC are seeded onto the hMSC-derived ECM matrices on TP and cultured under same oxygen condition.

All patents, patent applications, provisional applications, and publications referred to or cited herein are incorporated

by reference in their entirety, including all figures and tables, to the extent they are not inconsistent with the explicit teachings of this specification.

It should be understood that the examples and embodiments described herein are for illustrative purposes only and that various modifications or changes in light thereof will be suggested to persons skilled in the art and are to be included within the spirit and purview of this application and the scope of the appended claims. In addition, any elements or limitations of any invention or embodiment thereof disclosed herein can be combined with any and/or all other elements or limitations (individually or in any combination) or any other invention or embodiment thereof disclosed herein, and all such combinations are contemplated with the scope of the invention without limitation thereto.

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We claim:

1. A method for growing and/or expanding mammalian mesenchymal stem cell (MSC), the method comprising:
  - a) seeding freshly isolated mammalian MSC on a planar surface or a porous three-dimension (3-D) scaffold, wherein said surface or scaffold comprises one or more thermally responsive films or coatings;
  - b) growing said mammalian MSC under an O<sub>2</sub> tension that is lower than 20%;
  - c) decellularizing said surface or scaffold; and
  - d) reseeding said surface or scaffold with freshly isolated mammalian MSC, whereby said reseeded mammalian MSC grow and maintain an undifferentiated phenotype.
2. The method of claim 1, wherein said O<sub>2</sub> tension is between about 1% and 10%; or about 1% and 5%; or about 1% and 3%; or is about 2%.
3. The method of claim 1, wherein said decellularizing step is performed using a detergent and an enzyme that degrades nucleic acid.
4. The method of claim 1, further comprising the step of harvesting said reseeded MSC from said surface or scaffold.
5. The method of claim 1, wherein said mammalian MSC are human MSC.
6. The method of claim 1, wherein said mammalian MSC are isolated from bone marrow or adipose tissue of a mammal.
7. The method of claim 1, wherein said surface or scaffold is non-degradable.
8. The method of claim 1, wherein said surface or scaffold is composed of one or more of poly(styrene), poly(carpolactone), nylon, or poly(ethylene terephthalate) (PET).
9. The method of claim 1, wherein said reseeded cells are allowed to grow on said surface or scaffold for up to about three months.
10. The method of claim 1, wherein said thermally responsive film or coating comprises one or more of N-isopropyl-

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lacrylamide, poly(allylamine hydrochloride)-co-poly(N-isopropylacrylamide), or poly(styrene sulfonate)-co-poly(N-isopropylacrylamide).

11. The method of claim 1, wherein said one or more thermally responsive films or coatings comprises a terminal layer of positively charged allylamine hydrochloride (PAH), or negatively charged styrene sulfonic acid (PSS), or serum.

12. The method of claim 1, wherein said reseeded MSC are harvested from said surface by modulating the temperature of said thermally responsive film or coating to a temperature where cells adhered thereto are released.

13. The method of claim 12, wherein said harvested MSC are further grown and cultivated in suspension culture.

14. The method of claim 1, wherein said MSC are grown on said scaffold in a perfusion bioreactor.

15. The method of claim 1, wherein said MSC are grown in cell culture media comprising an animal serum at a concentration less than about 5% v/v or in serum-free cell culture media.

16. A composition comprising a decellularized extracellular matrix (ECM) prepared in vitro by:

- a) seeding freshly isolated mammalian MSC on a planar surface or a porous three-dimension (3-D) scaffold, wherein said surface or scaffold comprises one or more thermally responsive films or coatings;
- b) growing said mammalian MSC under an O<sub>2</sub> tension that is lower than 20%; and
- c) decellularizing said surface or scaffold.

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17. The composition of claim 16, wherein said O<sub>2</sub> tension is between about 1% and 10%; or about 1% and 5%; or about 1% and 3%; or is about 2%.

18. The composition of claim 16, wherein said decellularizing step is performed using a detergent and an enzyme that degrades nucleic acid.

19. The composition of claim 16, wherein said surface or scaffold is composed of one or more of poly(styrene), poly(carprolactone), nylon, or poly(ethylene terephthalate) (PET).

20. The composition of claim 16, wherein said thermally responsive film or coating comprises one or more of N-isopropylacrylamide, poly(allylamine hydrochloride)-co-poly(N-isopropylacrylamide), or poly(styrene sulfonate)-co-poly(N-isopropylacrylamide).

21. The composition of claim 16, wherein said one or more thermally responsive films or coatings comprises a terminal layer of positively charged allylamine hydrochloride (PAH), or negatively charged styrene sulfonic acid (PSS), or serum.

22. A composition comprising a decellularized extracellular matrix (ECM) prepared in vitro by:

- a) seeding freshly isolated mammalian MSC on a planar surface or a porous three-dimension (3-D) scaffold, wherein said surface or scaffold is composed of one or more of poly(styrene), poly(carprolactone), nylon, or poly(ethylene terephthalate) (PET);
- b) growing said mammalian MSC under an O<sub>2</sub> tension that is lower than 20%; and
- c) decellularizing said surface or scaffold.

\* \* \* \* \*

UNITED STATES PATENT AND TRADEMARK OFFICE  
**CERTIFICATE OF CORRECTION**

PATENT NO. : 9,220,810 B2  
APPLICATION NO. : 13/323475  
DATED : December 29, 2015  
INVENTOR(S) : Teng Ma and Junho Kim

Page 1 of 1


It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

In the specification

Column 2,

Line 23, "horning to sites" should read --homing to sites--.

Signed and Sealed this  
Twenty-ninth Day of November, 2016

A handwritten signature in black ink, reading "Michelle K. Lee". The signature is fluid and cursive, with the first letters of each name being capitalized and prominent.

Michelle K. Lee  
*Director of the United States Patent and Trademark Office*